Nuclear Engineering 282, UC Berkeley

Charged Particle Sources and Beam Technology

Particle Colliders (HEP), Spin Dynamics and Energy Calibration

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December 7, 2009

Today's Topics

- Colliders (High Energy Physics):
  - —Introduction
  - —Beam-Beam Interaction
  - —Examples of Colliders
  - —Energy Calibration
  - —Summary

- Lectures can be found at

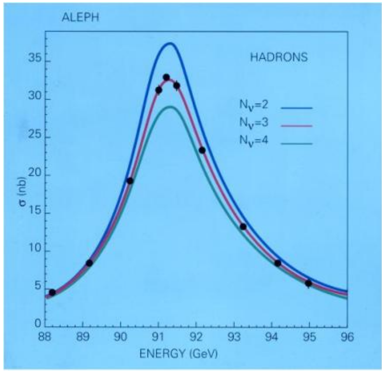
  http://als.lbl.gov/als_physics/robin/Teaching/NUC%20282c.html

Introduction

- Colliders for particle physics experiments are one of the most important application of accelerators.
- Developments in particle accelerators and elementary particle physics have evolved inc lose synergy.
- Colliders can be characterized by:
  - different nature of the colliding particles (leptons or hadrons)
  - different acceleration scheme used (linear or circular)
- In existing lepton colliders, electrons collide with positrons; significant R&D is underway for of a possible muon collider.
- Hadron colliders include protons colliding with protons or anti-protons and heavy ion colliders.
- Higher collision energies can be achieved with hadron colliders but “cleaner” measurements can be done with lepton colliders.

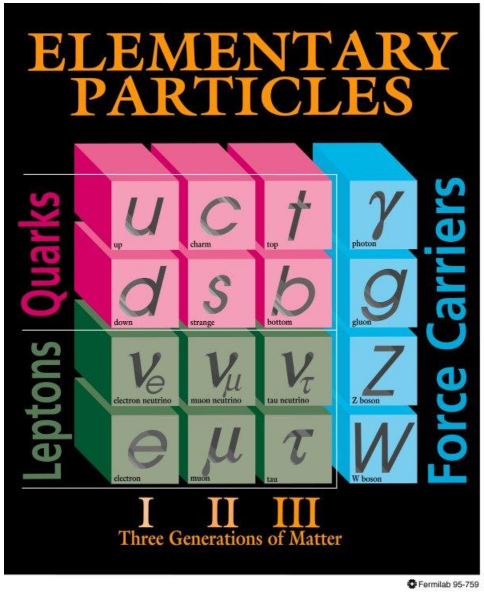
Introduction (2)

- In electron-positron collisions the particles annihilate and all the energy in the center of mass system is available for the generation of elementary particles.
- Such particle generation can happen only (except more complicated processes) if there is a particle with rest mass equal to the collision energy.
- The energy of the colliding beams can be tuned to the rest mass of a known particle for studying its properties, or can be scanned for the research of unknown particles.
- In hadron colliders, the quarks in the hadrons interact during the collision and generate other particles. Because each hadron is a combination of three quarks, simultaneous generation of many particles happens regularly.
- Most of the particles generated during a collisions have a short lifetime. Particle detectors are designed to measure the particle itself when possible or the particles generated during the decay.



Energy frontier: Particle Physics

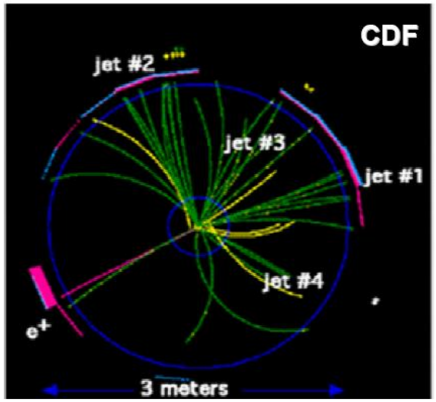
- For very long time particle physics has been driving accelerator development – higher and higher energies, while simultaneously higher luminosity
- Reasons:
  - —Resolution
  - —Particle production thresholds
- Particles once thought of as elementary have been shown to be composites …

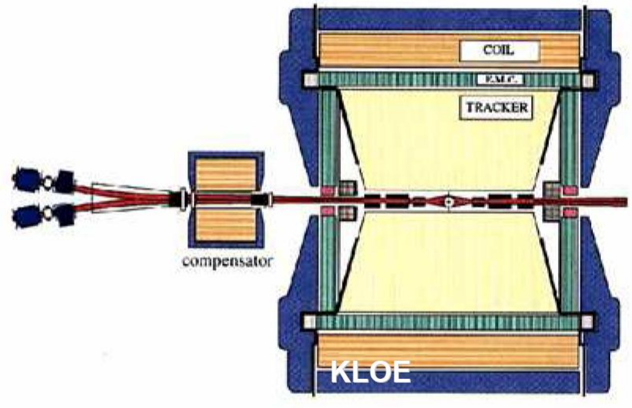


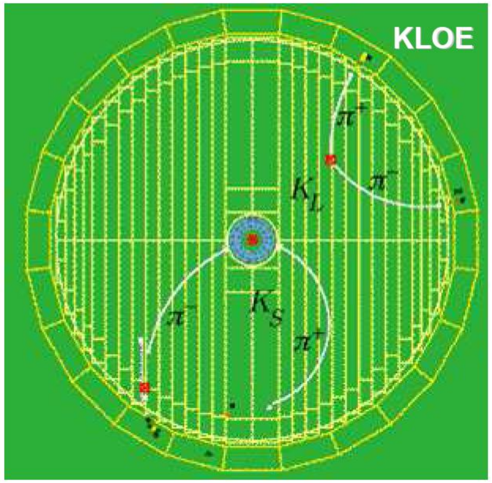
$$\lambda = \frac{h}{p}, \text{de Broglie wavelength}$$

$$E = mc^2, \text{Energy} - \text{mass relation (Einstein)}$$

Particle Physics Detectors







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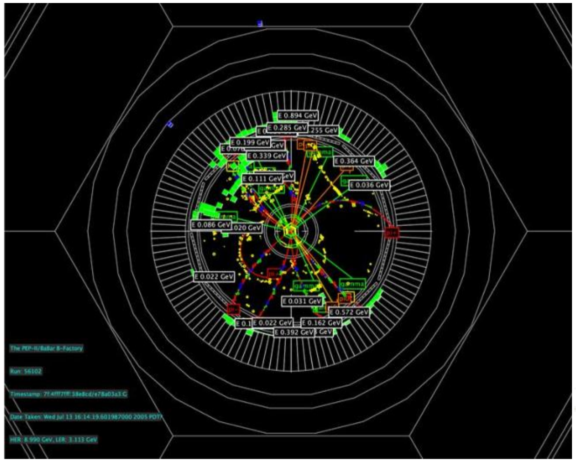
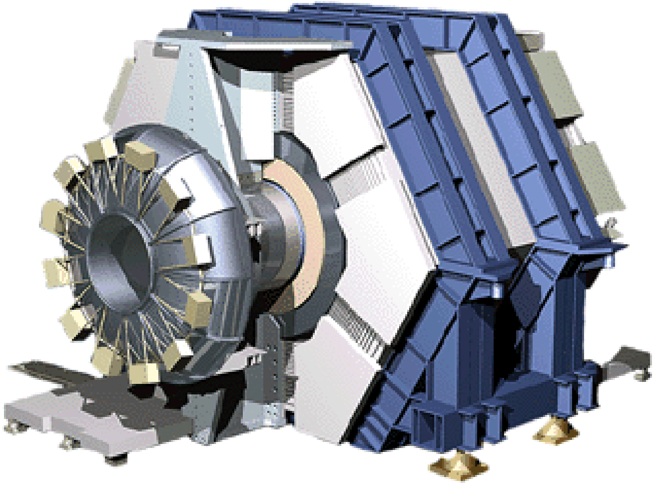
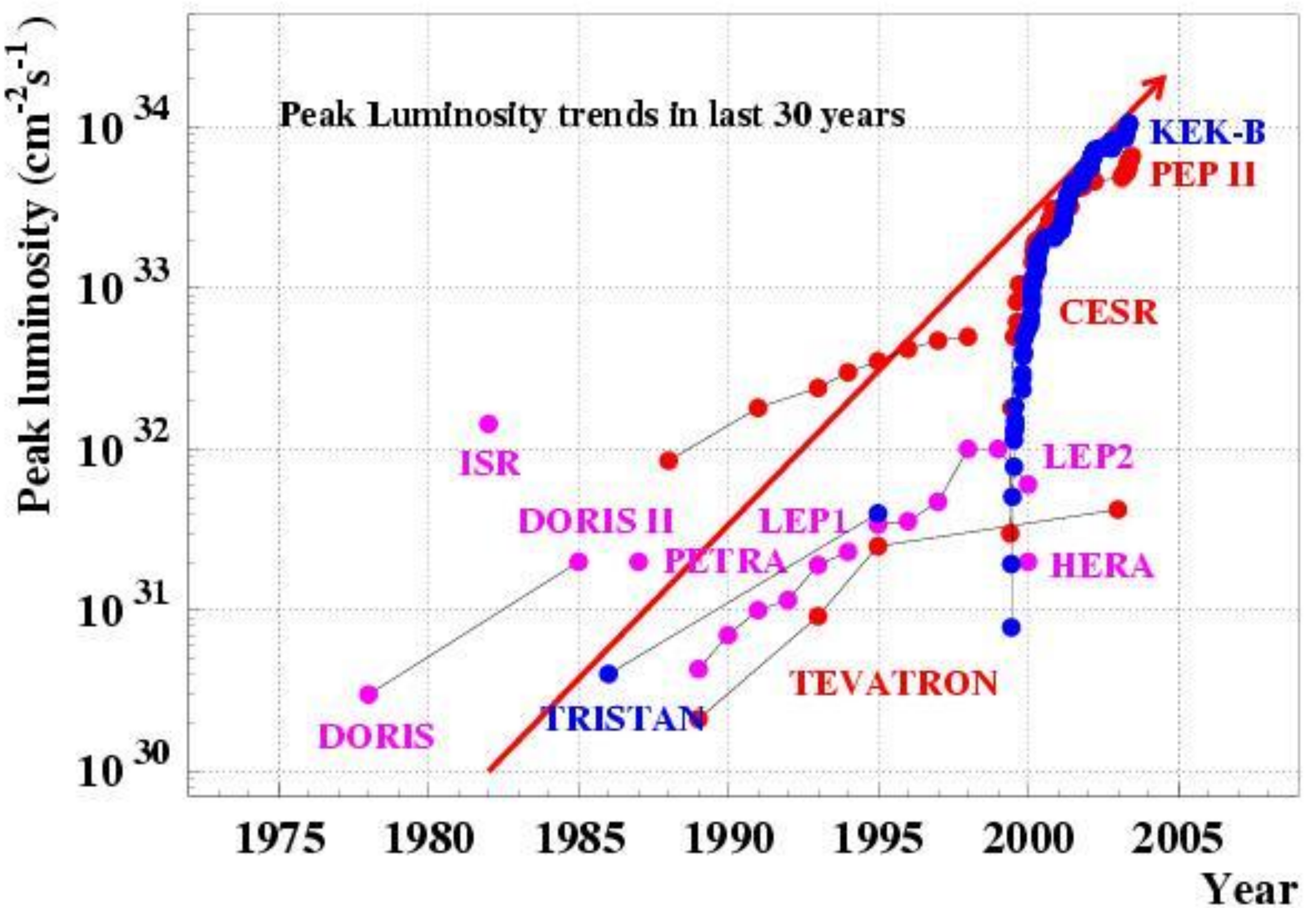


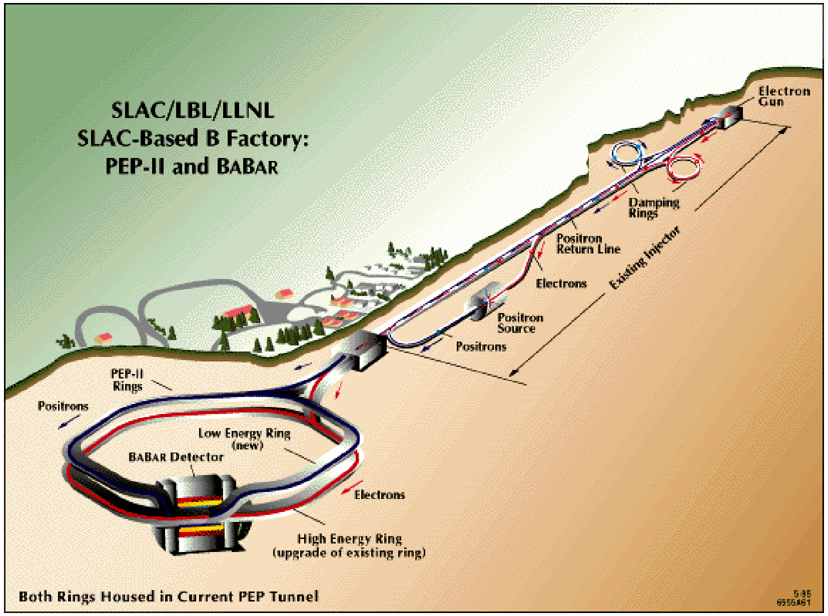


Key quantity for colliders: Luminosity



Very Brief History of Colliders

- The first collider to be used for experiments were the intersecting storage rings (ISR), used at CERN from 1971 to 1983.
- Several Nobel prizes were assigned for results obtained by accelerators (B. Richter and S. Ting 1976, C. Rubbia and S. van der Meer 1984)
- Modern example are the asymmetric B-factories PEP-II (SLAC, Stanford), KEK-B (Tsukuba, Japan) to study CP violation.
- Asymmetric configuration (P. Oddone, LBNL) allows spatial separation of decay vertices.



Center of Mass System (some special relativity)

- Two particles have equal rest mass m_0.

  Center of Mass Frame (CMF): Velocities are equal and opposite, total energy is E_{cm}.

$$P_1 = \left(E_{CM}/2c, p\right) \qquad P_2 = \left(E_{CM}/2c, -p\right)$$

Laboratory frame (LF):

$$\tilde{P}_1 = \left(E_1/2c, p_1\right) \qquad \tilde{P}_2 = \left(E_2/2c, p_2\right)$$

- The quantity $\left(P_1 + P_2\right)^2$ is invariant.
- In the CMF, we have $\left(P_1 + P_2\right)^2 = E_{CM}^2/c^2$
- While in the LF: $\left(\tilde{P}_1 + \tilde{P}_2\right)^2 = \tilde{P}_1^2 + \tilde{P}_1^2 + 2\tilde{P}_1\tilde{P}_2 = 2m_0^2c^2 + 2\tilde{P}_1\tilde{P}_2$
- And after some algebra we can obtain for relativistic particles:

$$\boxed{E_{cm} \cong 2\sqrt{E_1 E_2}}$$

Cross Sections - Luminosity

Cross Section:

Event Rate
per Unit Incident Flux
per Target Particle

Luminosity:

Event Rate
for a
Unit Cross Section Event

Luminosity

$$n_{\pm}(x,y,z,t)$$

$$\iiint dx\,dy\,dz\; n_{\pm}(x,y,z,t) = N_{\pm}$$

- Single Bunch
- Head-on Collision
- Counter-rotating Beams with Longitudinal Speed v
- Revolution Frequency f_R

$$L = 2\,v\,f_R \iiiint dx\,dy\,dz\,dt\; n_+(x,y,z,t)\,n_-(x,y,z,t)$$

Luminosity (gaussian beams)

$$n_-(x,y,z,t) = N_- \frac{e^{-\frac{x^2}{2\sigma_{x-}^2}-\frac{y^2}{2\sigma_{y-}^2}-\frac{(z-vt)^2}{2\sigma_{z-}^2}}}{(2\pi)^{3/2}\sigma_{x-}\sigma_{y-}\sigma_{z-}} \qquad n_+(x,y,z,t) = N_+ \frac{e^{-\frac{x^2}{2\sigma_{x+}^2}-\frac{y^2}{2\sigma_{y+}^2}-\frac{(z+vt)^2}{2\sigma_{z+}^2}}}{(2\pi)^{3/2}\sigma_{x+}\sigma_{y+}\sigma_{z+}}$$

$$\sigma_{x\pm}, \sigma_{y\pm} \equiv \text{constants}$$

$$L = f_R \frac{N_+ N_-}{2\pi\sqrt{\left(\sigma_{x+}^2 + \sigma_{x-}^2\right)\left(\sigma_{y+}^2 + \sigma_{y-}^2\right)}}$$

$$L = f_R \frac{N_+ N_-}{4\pi\ \sigma_x \sigma_y}$$

$$\sigma_{x+} = \sigma_{x-} \qquad \sigma_{y+} = \sigma_{y-}$$

How to optimize Luminosity

- **Luminosity can be optimized by making the beam sizes small, increasing the charge per bunch or increasing the bunch frequency – limits to all of those methods.**

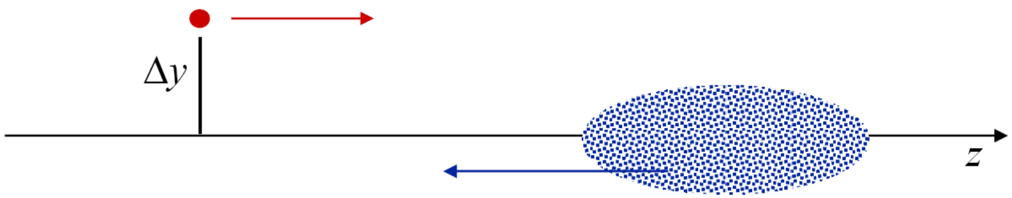
Charge Related Effects:

Or *beam-beam* effects. Charge plays a major role, limiting the achievable luminosity in most of storage ring colliders.

Geometric Effects:

How the "geometry" of the interaction point (IP) and the size of the beams affect luminosity

Beam-Beam Effects



For a gaussian charge distribution:

$$\Delta y' = -\frac{2 N r_e \Delta y}{\gamma} \int_0^\infty \frac{\exp\left(-\frac{\Delta x^2}{2\sigma_x^2 + w} - \frac{\Delta y^2}{2\sigma_y^2 + w}\right)}{\left(2\sigma_y^2 + w\right)^{\frac{3}{2}} \left(2\sigma_x^2 + w\right)^{\frac{1}{2}}} dw$$

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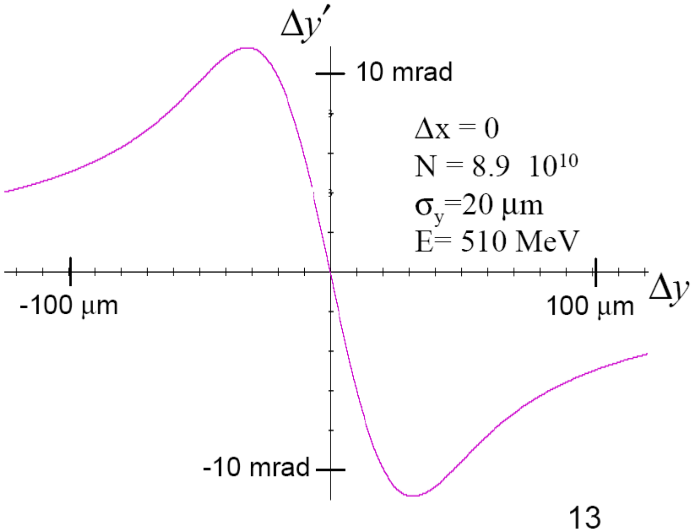
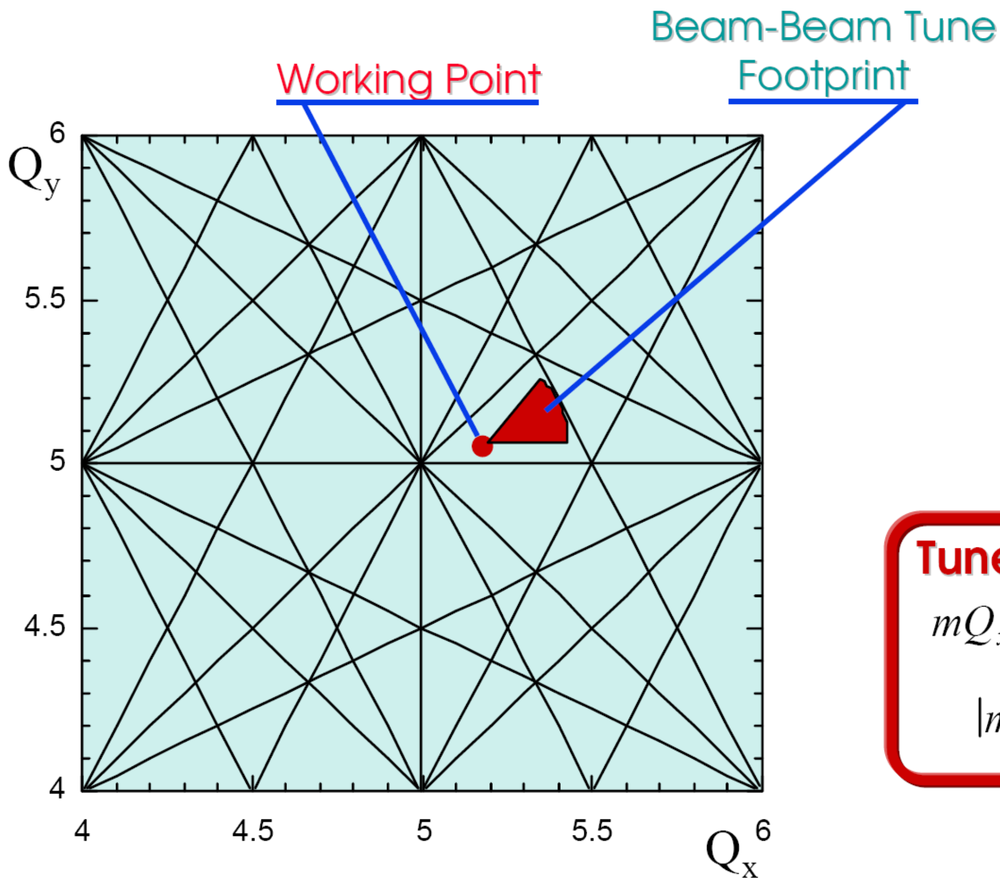


Beam-Beam Tuneshift



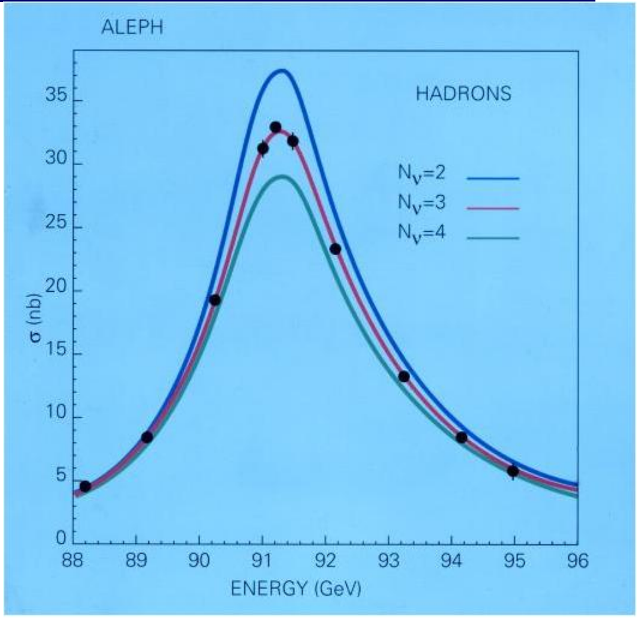
Tune Resonances

$$mQ_x + nQ_y = p \qquad m,n,p \in \mathbf{N}$$

$$|m| + |n| = resonance \quad order$$

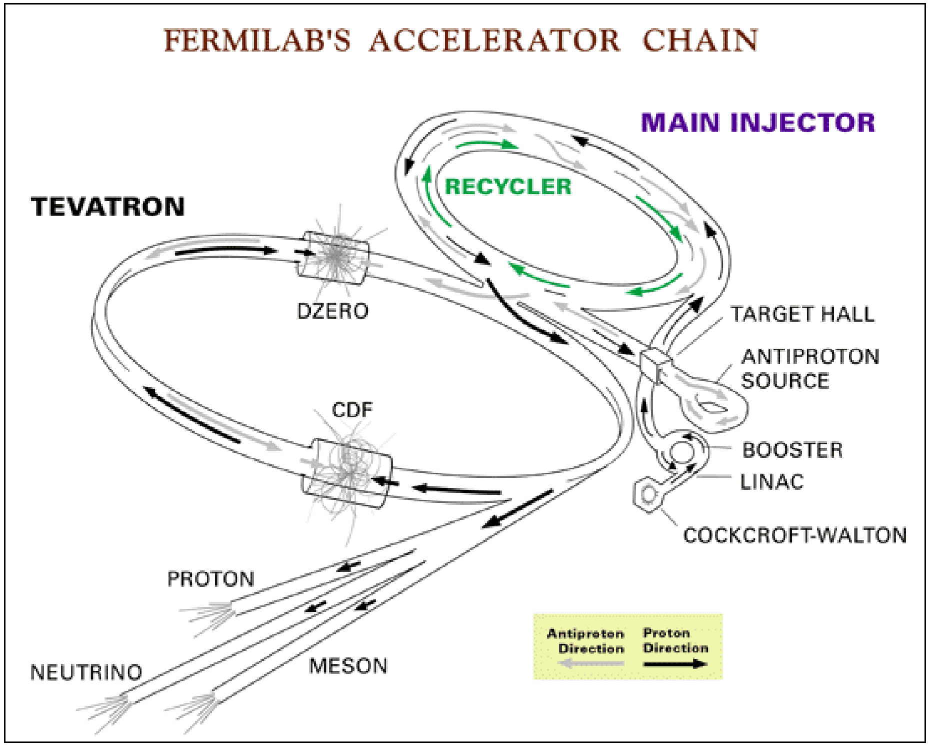
- **Resonances were explained in transverse dynamics lectures earlier in series.**

Examples of Colliders



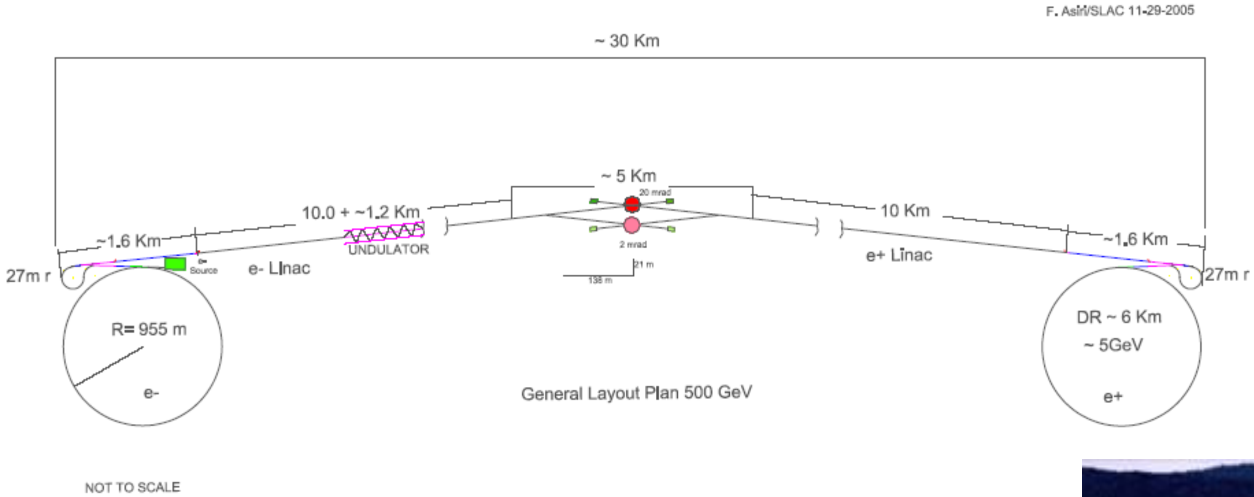
At CERN in Geneva, Switzerland is the world's largest accelerator: Until 2000 – LEP (electron positron) – electroweak precision measurements. Currently under construction: LHC (7x7 TeV) – Higgs, …

Examples of Colliders (2)



Tevatron at Fermilab, near Chicago, IL, is currently the world's highest energy accelerator (about 1x1 TeV). Protons – Antiprotons. Main emphasis is Higgs and search of physics beyond Standard model.

Examples of Linear Colliders



ILC (planned)

SLAC (Stanford)

- Linear Colliders mostly avoid problem of
  - Beam-Beam effects
  - Synchrotron Radiation
- However:
  - Accelerating sections only used once
  - Produced particles only used once

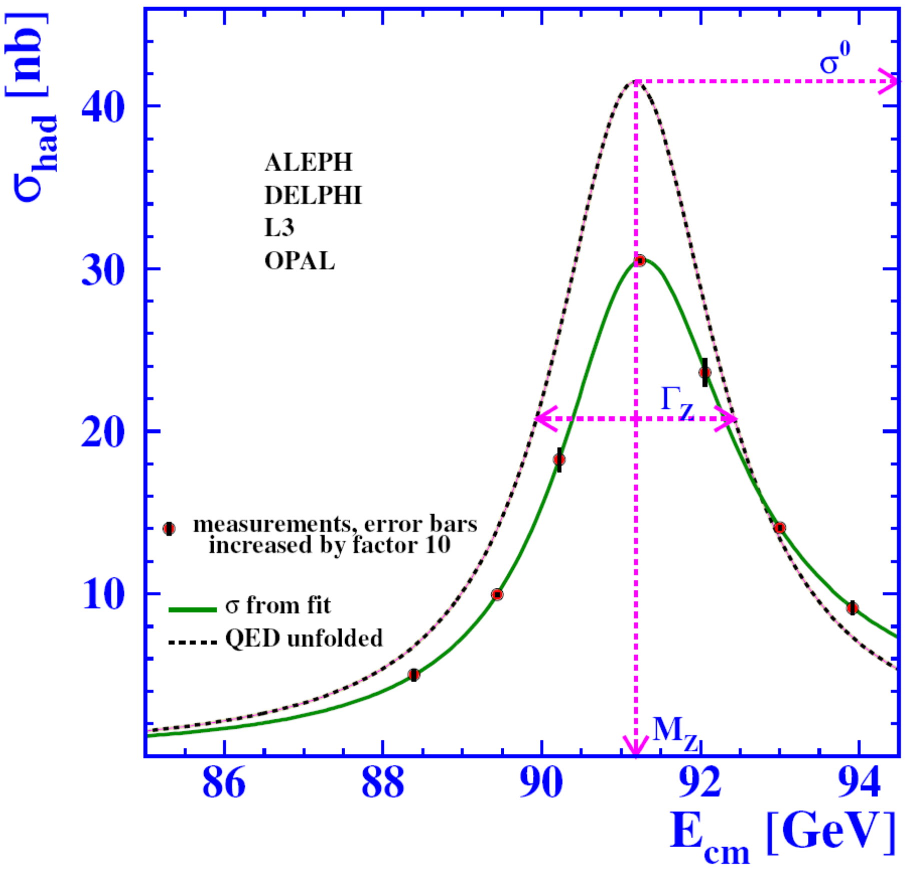
Energy Calibration (Motivation)

Improvement of the determination of particle masses
obtained from resonant depolarization of polarized e^+e^- beams

Particle	World average value (MeV)	Experimental results (MeV)	Year publication	Accuracy improvement
$K^\pm$	493.84 ± 0.13	493.670 ± 0.029	1979	5
K^0	497.67 ± 0.13	497.661 ± 0.033	1987	4
ω	782.40 ± 0.20	781.780 ± 0.10	1983	2
ϕ	1019.7 ± 0.24	1019.52 ± 0.13	1975	2.5
J/ψ	3097.1 ± 0.90	3096.93 ± 0.09	1981	10
ψ'	3685.3 ± 1.20	3686.00 ± 0.10	1981	10
Υ	9456.2 ± 9.50	9460.59 ± 0.12	1986	80
Υ'	10016.0 ± 10.	10023.6 ± 0.5	1984	20
Υ''	10347.0 ± 10.	10355.3 ± 0.5	1984	20

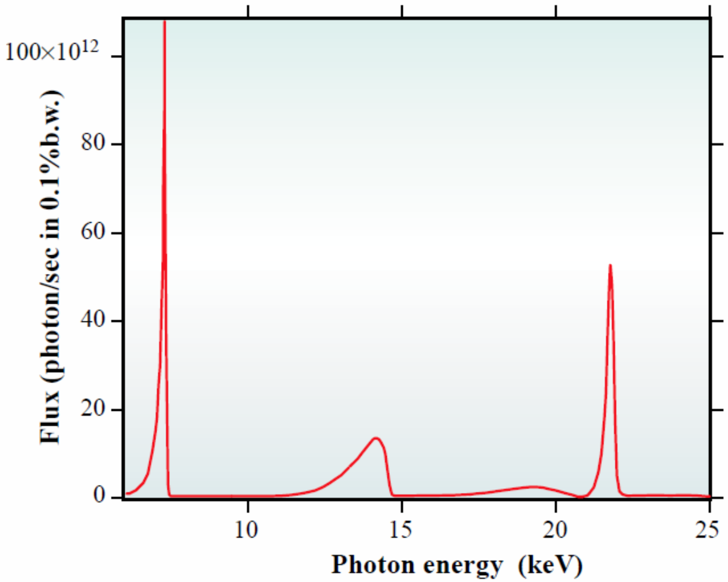
- Using resonant depolarization allows an ultra high precision measurement of the beam energy
- Many applications: precise determination of particle masses, ...

Main Physics Result (LEP)



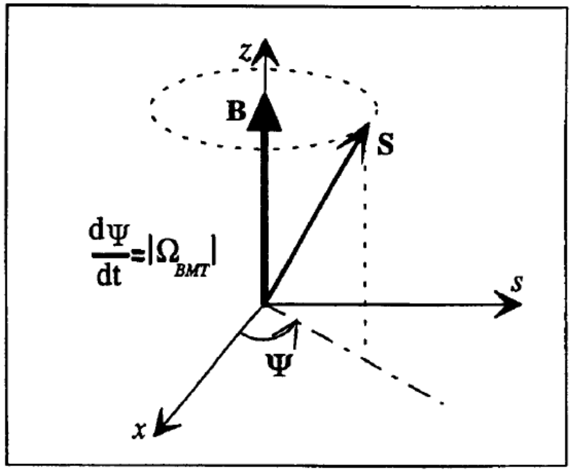
- ❑ Using resonant depolarization allows an ultra high precision measurement of the beam energy
- ❑ Another application: resonance linewidths. Example of LEP: Precision measurement of Z_0 width allowed conclusion that only 3 lepton families with light neutrinos exist.

Motivation



- In terms of accelerator physics it is often important to know beam energy precisely (cross check of magnetic measurement data, direct measurement of momentum compaction factor with high resolution).
- At synchrotron light sources a reasonable stability of the beam energy is important (energy stability of undulator beams, etc.) which can be verfied with resonant depolarization.

How Does It Work



- Spin motion of non radiating electron $\Rightarrow$ BMT-equation:

$$\frac{d\vec{S}}{ds} = \vec{\Omega}_{\text{lab}} \times \vec{S}$$

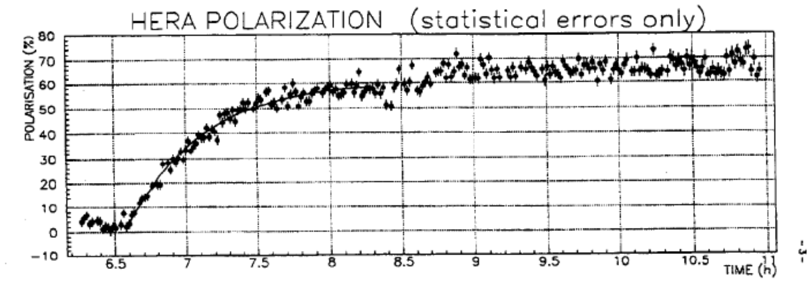
for $\gamma \gg 1$

$$\vec{\Omega}_{\text{lab}} = \frac{e}{m_e\, c\, \gamma_{\text{lab}}} \left((1+a)\vec{B}_{||} + (1+\gamma_{\text{lab}} a)\vec{B}_{\perp} \right)$$

a: gyromagnetic anomaly $a = 1.159652 \cdot 10^{-3}$ for electrons and 1.792846 for protons

- flat ring $\Rightarrow$ $\nu_{sp} = \gamma a$
- only vertical component of spin is stable

How Does It Work (2)



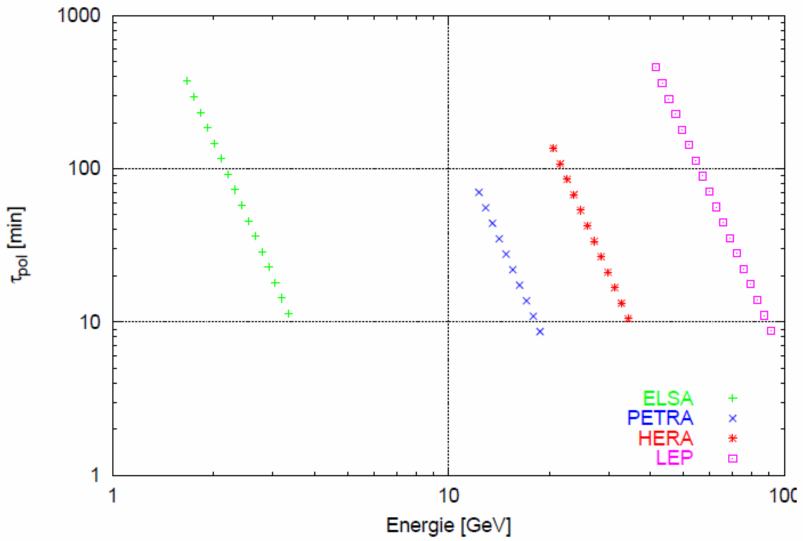
	VEPP[10]	VEPP2-M[11]	ACO[8,9]	BESSY[44]	SPEAR[45]	VEPP4[46]
E(GeV)	0.640	0.625	0.536	0.800	3.70	5.0
τ_p(min)	50	70	160	150	15	40
P(%)	52	90	90	>75	>70	80
	DORIS II[47]	CESR[48]	PETRA[49]	HERA[19]	TRISTAN[50]	LEP[51]
E(GeV)	5.0	4.7	16.5	26.7	29	46.5
τ_p(min)	4	300	18	40	2	300
P(%)	80	30^*	80^{**}	70^{**}	75^{**}	57^{**}

- radiating leptons $\Rightarrow$ polarization buildup (Sokolov-Ternov effect):

$$P = A\left(1 - e^{-\frac{t}{\tau_{\mathrm{pol}}}}\right), \quad \frac{1}{\tau_{\mathrm{pol}}} = \frac{5\sqrt{3}}{8}\,\frac{c\lambda_c r_e}{2\pi}\,\frac{\gamma^5}{\rho^3}$$

- has been observed at most lepton storage rings that have looked for the effect.

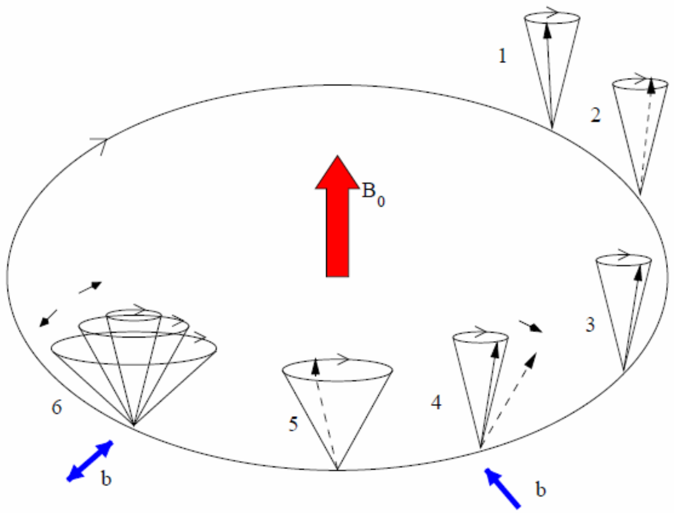
Typical Polarization Buildup Times



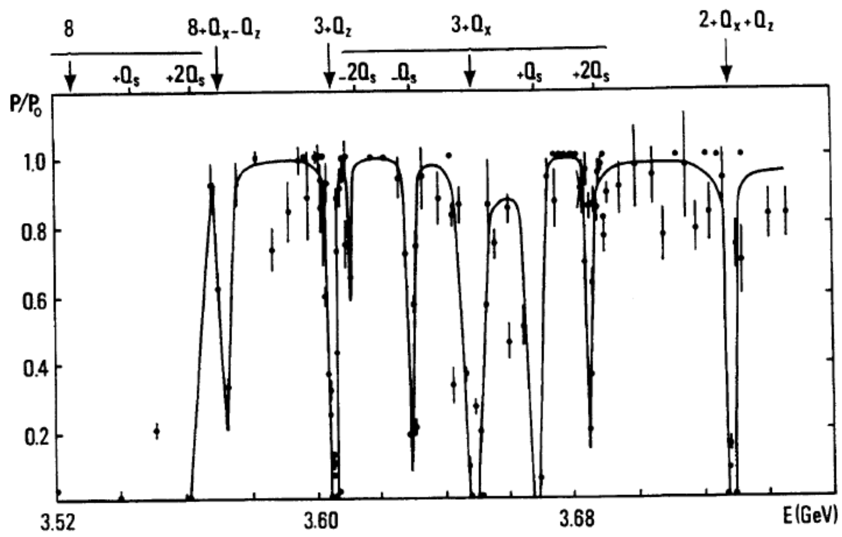
- Even though the polarization buildup time for a given ring strongly depends on the beam energy, it has about the same order of magnitude for most lepton storage rings.
- Reason is that it also scales with the bending radius and machines with higher energy typically have to have much larger bending radius to keep equilibrium emittance small and SR losses acceptable.

Depolarizing Resonances

- Depolarization due to resonant coupling of spin precession with horizontal magnetic fields
- intrinsic resonances: vertical betatron oszillations $\Rightarrow$ horizontal magnetic fields in quadrupoles (and sextupoles ...)
  resonance condition: $\gamma a = (kP \pm Q_z)$
- imperfection resonances: magnet errors (field- and position errors) $\Rightarrow$ closed orbit distortions
  resonance condition: $\gamma a = k$
- weaker resonances: gradient errors, coupling, sextupoles, synchrotron satellites

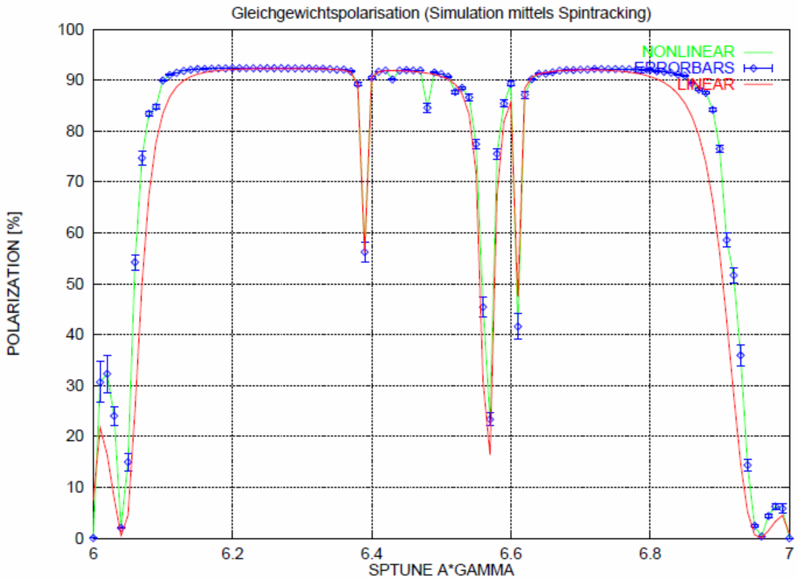


Equilibrium Polarization and Depolarizing Resonances



- Equilibrium of self polarization and resonances depends on energy.
- Resonance strength increases with energy.
- Imperfection resonance strength scales with the closed orbit error
- Intrinsic resonance strengths scales with the vertical emittance

Simulations of Equilibrium Polarization



- Using spin tracking codes, one can calculate the equilibrium between polarizing and depolarizing effects.
- Using the simulations, one can optimize the correction techniques (orbit correction, harmonic spin matching, coupling correction, ...)
- Correction is much faster, if one has a good model of the machine lattice (predictive spin mathcing).

Polarimeters

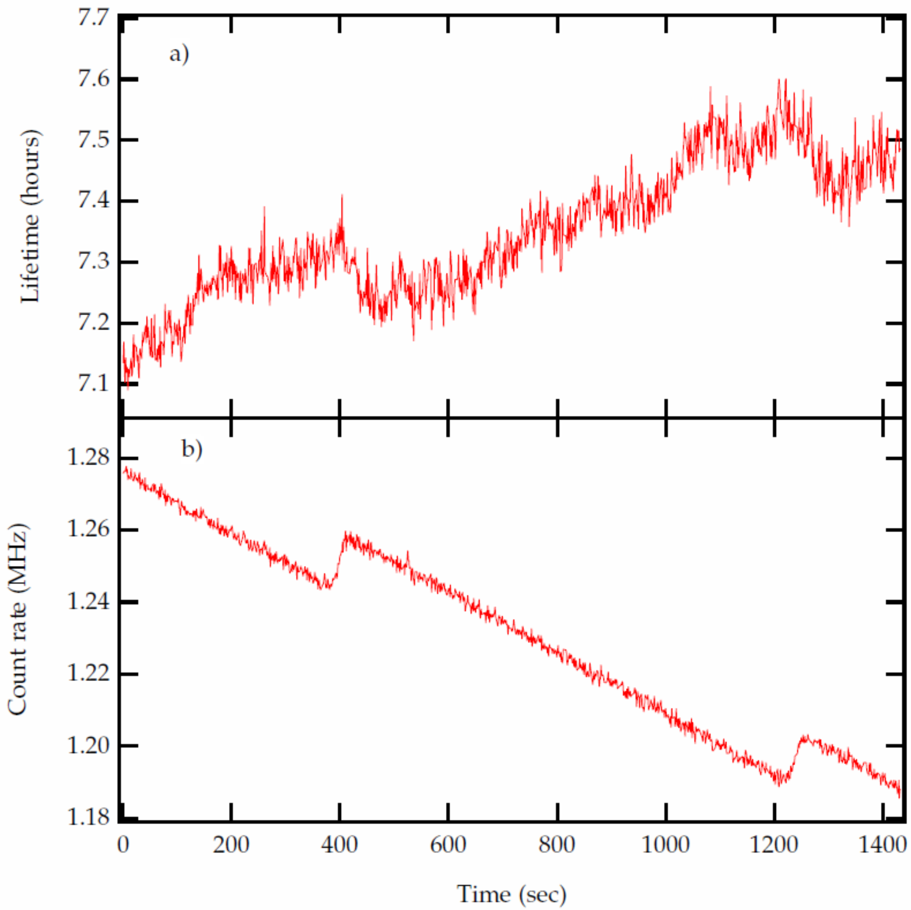
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega} \cdot \left(1 + P_T P_B A_{zz}(\theta)\right)$$

$$\frac{d\sigma_0}{d\Omega} = \left[\frac{\alpha(4-\sin^2\theta)}{2E_e^{CMS}\sin^2\theta}\right]^2$$

$$A_{zz}(\theta) = \frac{(-\sin^2\theta)(8-\sin^2\theta)}{(4-\sin^2\theta)^2}$$

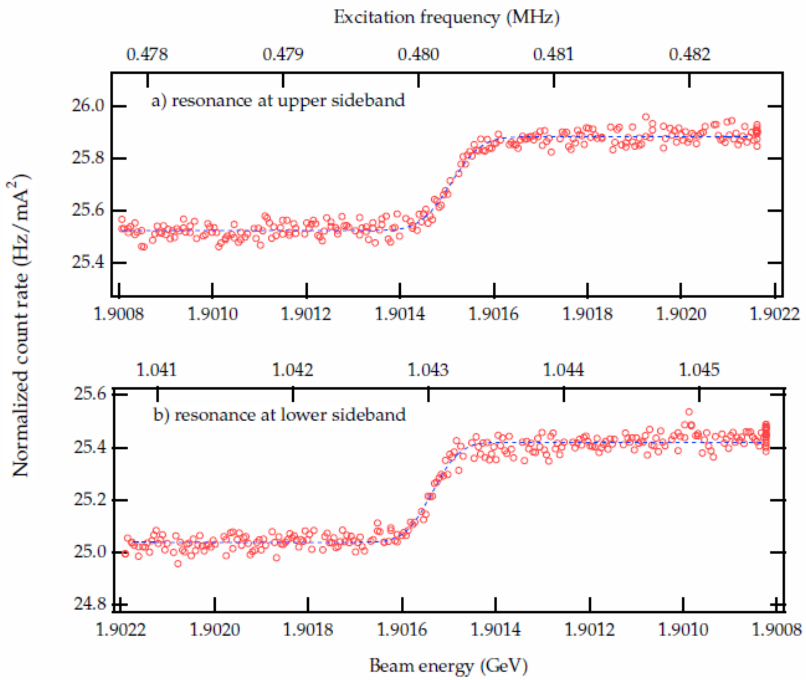
- All polarimters use asymmetry in scattering cross sections
- Compton-polarimeters (laser photons hitting beam, spatial asymmetry in backscattered photons), Møller polarimeters (polarized electrons on polarized electrons mostly in target foils), Mott polarimeters, ...
- Storage rings typically use Compton polarimeters (nearly non-destructive).
- If Touschek lifetime contribution is significant one can use simple polarimeter: Touschek scattering is Møller scattering. Møller scattering cross section depends on polarization (polarized beams have longer Touschek lifetime!).
- depolarization reduces Touschek lifetime by up to 20%

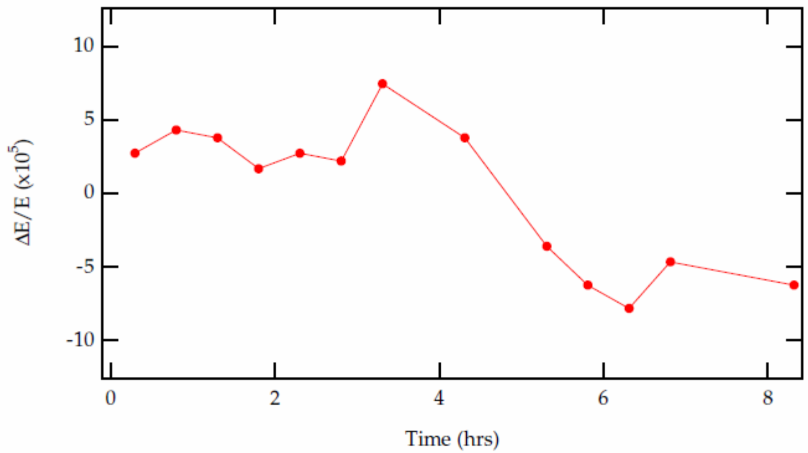
Example: ALS – Touschek Lifetime



- Møller scattering cross section depends on polarization
- depolarization changes (reduces) Touschek lifetime by up to 20%
- experimentally simple: stripline kicker for tune measurement is sufficient + gamma telescope
- partial depolarization allows for 'fast', multiple measurements

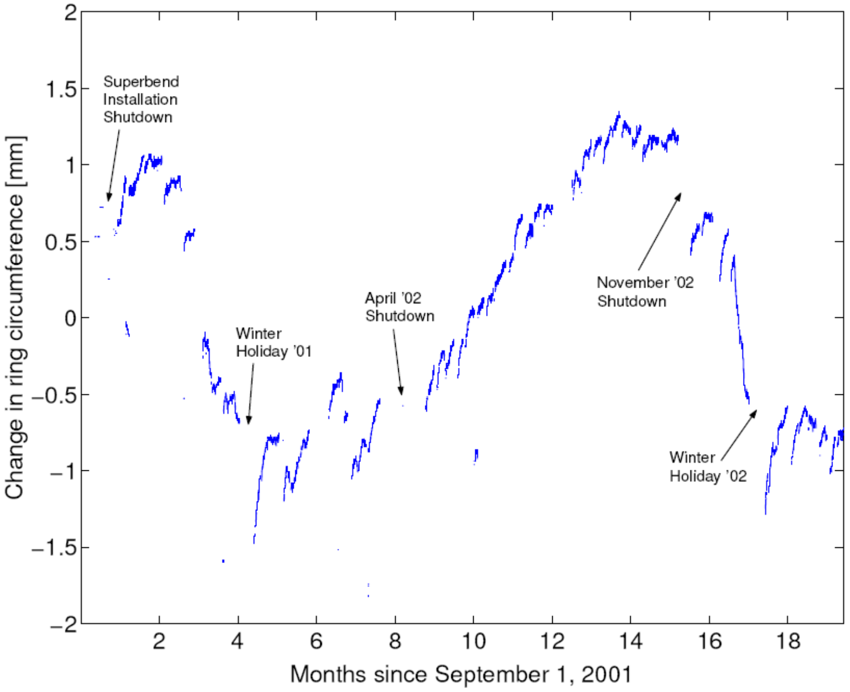
ALS Example ctd.





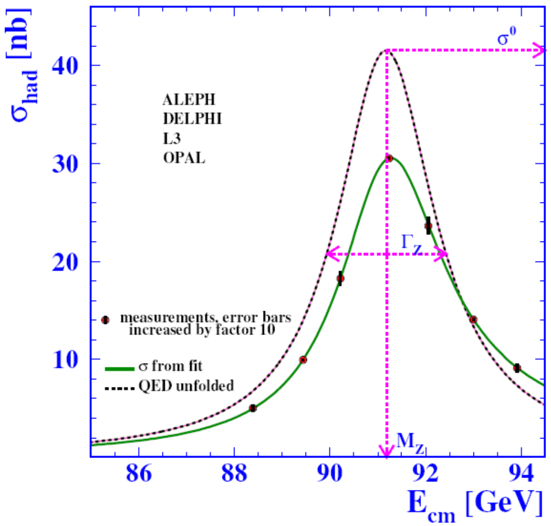
- partial depolarization allows better accuracy in sweeping measurements
- energy stable to a about $\pm 1 \cdot 10^{-4}$ within a week without rf-frequency feedback - much better with ...

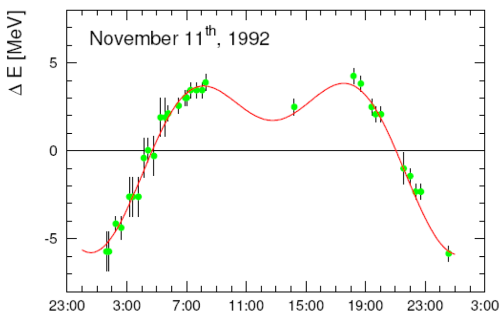
Effects that Change the Energy



- Circumference of ring changes (temperature inside/outside, tides, water levels, seasons, differential magnet saturation,)
- RF keeps frequency fixed - beam energy will change
- Instead measure dispersion trajectory and correct frequency (at ALS once a second)
- Can see characteristic frequencies of all the effects in FFT (8h, 12h, 24h, 1 year)
- Verified energy stability (a few 10^{-5}) with resonant depolarization

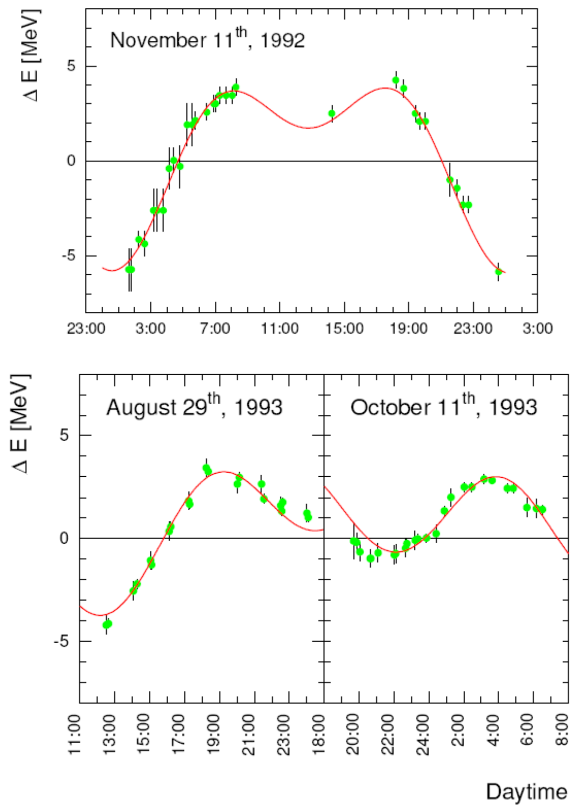
Back to Application (LEP)





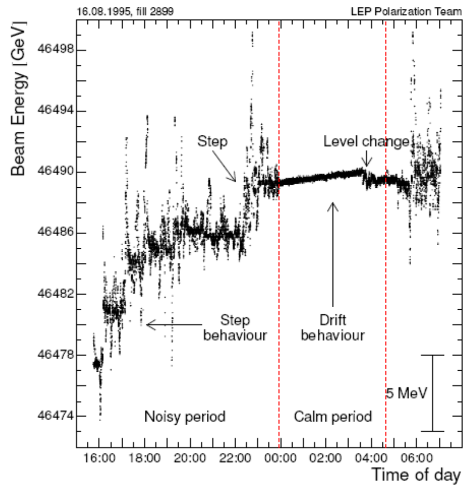
- Many electroweak precision measurements
- Precise energy calibration essential
- Found many interesting effects: Tides, Lake Geneva, TGV, ...

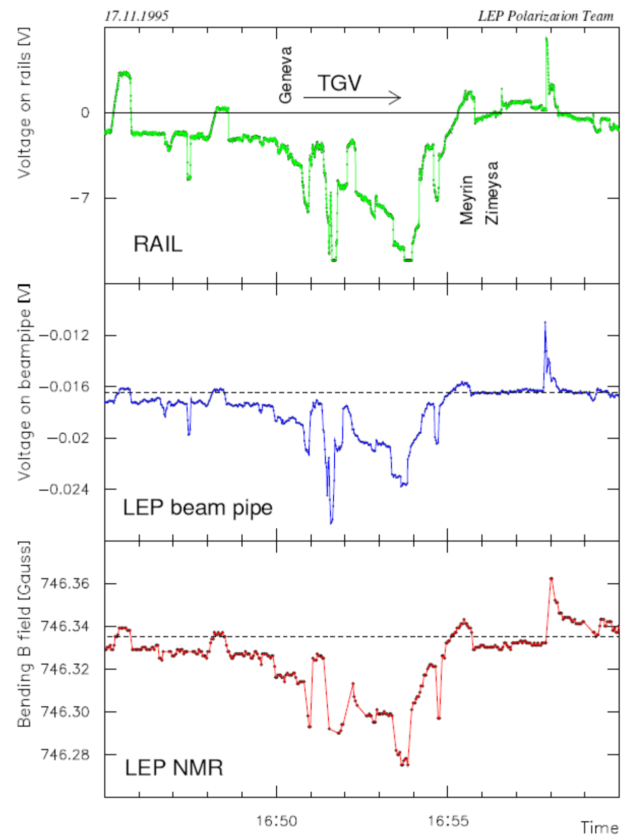
Tides at LEP



- Average tides of oceans about 0.5 m (locally much larger)
- Average tidal variation of solid ground about 1/3 of that!
- Tides cause local change in earth radius - change in ring circumference - beam energy change (scales only with momentum compaction factor, not with the size of the machine - effect is about equally strong at light sources like ESRF as it was ta LEP).
- For LEP this was very significant effect, far larger than precision of energy needed
- Measurements with resonant depolarization agreed very well with tidal predictions

The TGV …

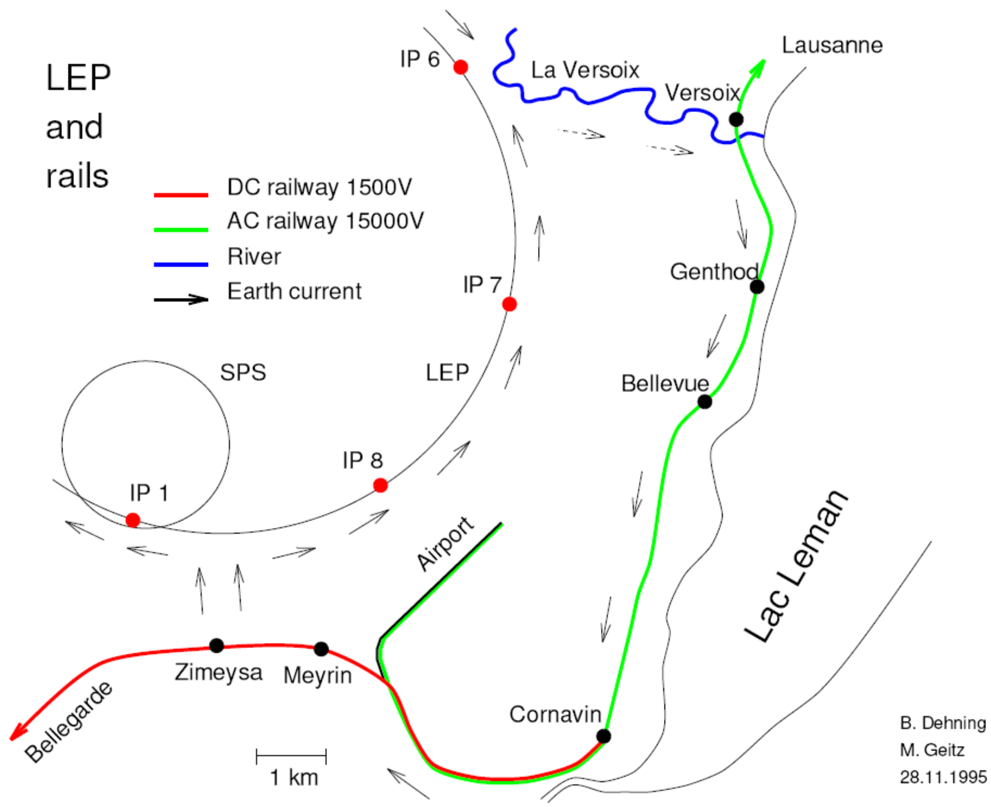




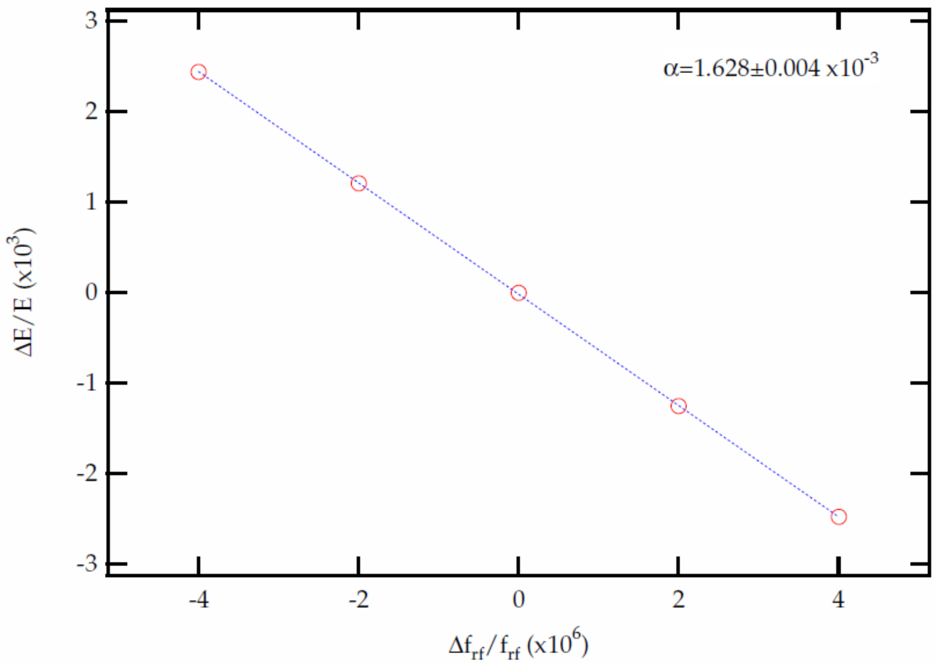
- Large noise in magnetic dipole field found
- Stopped overnight
- Intensive search - accidental discovery (on French holiday)
- Return currents of TGV

The TGV: explanation

- Measured distribution of current on LEP vacuum chamber
- Reconstructed path of return currents from TGV

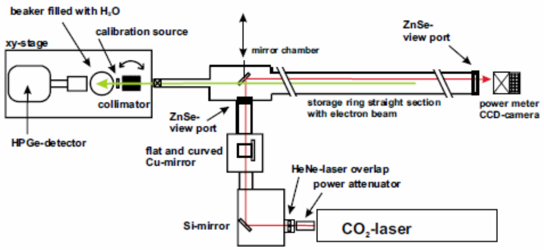


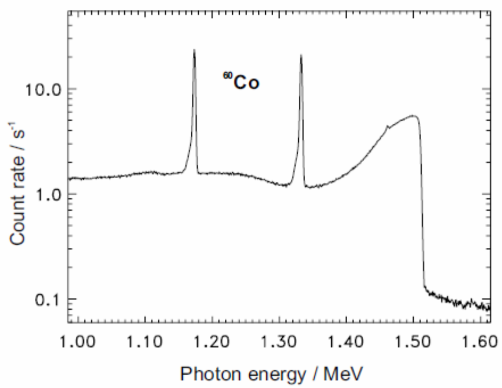
Another ALS example: Momentum Compaction Factor



- resonant depolarization allows a precise measurement of the momentum compaction factor
- $\alpha = (1.628 \pm 0.004) \cdot 10^{-3}$
- for some machines, it could be used to measure nonlinear α terms

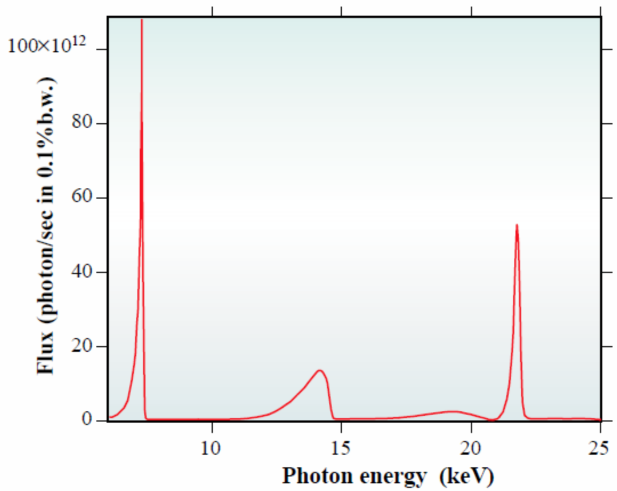
Other Methods of Energy Measurements





- Measuring energy spectrum of compton backscattered (laser) photons
- high energy edge is well defined (laser photon energy + γ^2 Lorentz boost)
- Addition of line spectrum from radioactive decay allows easy online calibration
- Advantage is relatively fast measurement - No polarizatiob necessary
- Disadvantage is lower precision

Other Methods (2)



- Measuring the photon energy spectrum from an undulator allows fast beam energy measurement (with moderate resolution)
- Magnetic field data of undulator has to be very well known
- Monochromator has to be well understood
- Another possibility is to caclulate the beam energy based on magnetic measurements (either off-line or on-line with NMR probes) plus the readings of BPMs

Summary

- Colliders are one of the most important accelerator categories – historically close synergy between particle physics and accelerator physics
- Very complex machines – many effects to consider for optimized design/operation
- Very successful: Exponential growth of beam energy and luminosity with time
- Energy calibration is an ultra precise tool revealing the small results of everyday disturbances

Thanks to Fernando Sannibale for several of my slides